Study on Motion Suppression Systems Applied to Floating Structures for Coastal Development

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1. INTRODUCTION

Floating structures influence the surroundings less and are more earthquake resistant in comparison with land reclamation. For the effective utilization of ocean space along coastal areas, it is necessary to expand the use of floating structures.

The Coastal Development Institute of Technology has collaborated with Mitsubishi Heavy Industries, Ltd. on a study of motion suppression systems applied to small- and medium-sized floating structures, such as floating piers and work vessels, from the aspect of technology in the fiscal years 1997 to 1999.

Movement of floating structures is one of their most undesirable characteristics as it causes discomfort and danger to people, danger in cargo handling and device damage, and increases the maintenance costs.

In order to effectively attain better performance, several well-known concepts of motion suppression in the design of ships and high-rise structures were adopted and validated by means of theoretical calculations and model tests.

2. PROPOSED ROLL SUPPRESSION METHODS

Small- and medium-sized floating structures with the length of 100m or less and the breadth of 25m or less were chosen as the subject of this study. In these cases, rolling motion is dominant. Therefore, roll suppression methods were investigated in the present study.

Passive-type methods with no power requirements were basically examined, taking cost effectiveness into consideration. The environmental conditions in a moderate inland sea area, including the effect of a wave train generated by a passing ship, were specified; the wave period to be dealt with is as 4 to 6s or shorter, as shown in Table 1. The basic hull form in this study is a cubic pontoon. Its main dimensions are shown in Table 2.

Table 1 Specified environmental condition

Water depth	10 m
Significant wave height $H_{1/3}$	0.5 m
Significant wave period $T_{1/3}$	4 ~ 6 s

Table 2 Main dimensions of the basic hull

Length	L	70 m
Breadth	B	15 m
Depth	D	3.2 m
Draft	d	2.2 m
Displacement	Δ	2368 ton
Height of C. G.	KG	1.62 m
Metacentric height	GM	8.0 m
Natural period of roll	T_{roll}	4.6 s

The following four designs were selected

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from many roll suppression designs[1], on the basis of the examination by theoretical calculations based on potential theory. Fig. 1 shows the main transverse section of each design.

(1) SWAF (Small Waterplane Area with Fin) [2,3]

This hull shape has a reduced waterplane area and a bottom fin along its entire length. It has features nearly the same as those of the well-known semisubmersible form. This hull form is referred to as SWAF in this paper.

The good motion characteristics of this hull form are derived from a combination of the low initial metacentric height GM and the small waterplane area. The well-known formula for estimating the natural period of roll is

$$T_{roll} = 2\pi \sqrt{\frac{I_{44} + A_{44}}{g\Delta\, GM}} \qquad (1)$$

,where $I_{44,}$ A_{44} and Δ are mass moment of inertia, added mass moment of inertia and displacement, respectively. The result is an increase in the natural roll period which leads to a shift in the roll response curve toward higher periods.

The semisubmersible-like hull form produces the small wave excitation moment of roll.

(2) SLO-ROL [4,5]

The damping tank system called SLO-ROL consists of tanks placed along the side of the main hull. The tanks are located on the outside of the hull like lower sponsons. These tanks are open to the sea at the bottom and the port and starboard tanks are connected to air ducts.

The SLO-ROL tanks are activated by half-filling them with compressed air using for example, a blower. The air-filled SLO-ROL tanks radically alter the roll performance of the hull due to the reduced metacentric height GM. The main factor effect of the system is the increase of the natural roll period due to the reduced metacentric height GM. The GM reduction rate is derived from

$$\delta(GM)\,/\,GM = 2\rho g \ell_t^{\,2} S_t \,/(\Delta\, GM) \qquad (2)$$

,where ℓ_t and S_t are the transverse distance of the tank from the center of gravity and the waterplane area of each side tank, respectively. The SLO-ROL tank has a very large $\delta(GM)\,/\,GM$ ratio of about 0.6.

The outward hull form of SLO-ROL is like that of the above-mentioned SWAF. Therefore, a very large increase in the natural roll period is produced due to the combination of the effect of the SLO-ROL tanks and the SWAF hull form.

The damping effect of the SLO-ROL tanks can be changed by adjusting the orifice of the air duct. The optimized damping reduces the peak values of the roll response amplitude in the natural period.

(3) ART (Antiroll Tank) [6,7]

Passive antiroll tanks have been installed on many ships. There are two types of ART: U-tube tanks and free-surface tanks. In the present study, the free-surface tanks are used. By changing the water level in the tanks, it is possible to change the resonance period of the free-surface tanks. In order for the ART to be effective, it is necessary for the natural period of water motion in the tank to be close to the natural period of roll motion. The highest natural period of a rectangular free-surface tank can be written as

$$T_{\tanh} = \frac{2\pi}{\sqrt{(\pi g/b)\tanh(\pi h/b)}} \qquad (3)$$

,where h is the water depth in the tank and b is the breadth of the tank. The ART has a $\delta(GM)\,/\,GM$ ratio of about 0.1.

The proposed location of the tank is above the deck and it functions as the roof as shown in Fig. 1. The damping factor for water motion in the tank can be adjusted to be an optimum value by changing the quantity of additional resistance.

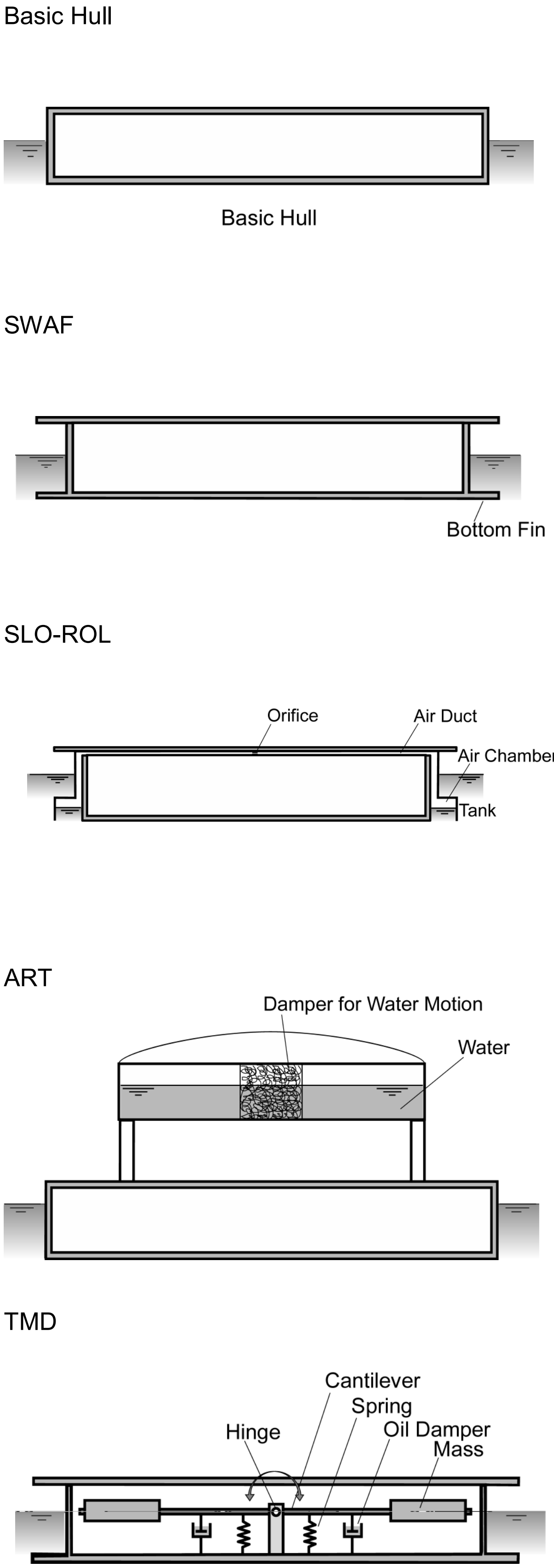

Fig. 1 Main transverse sections of the concepts

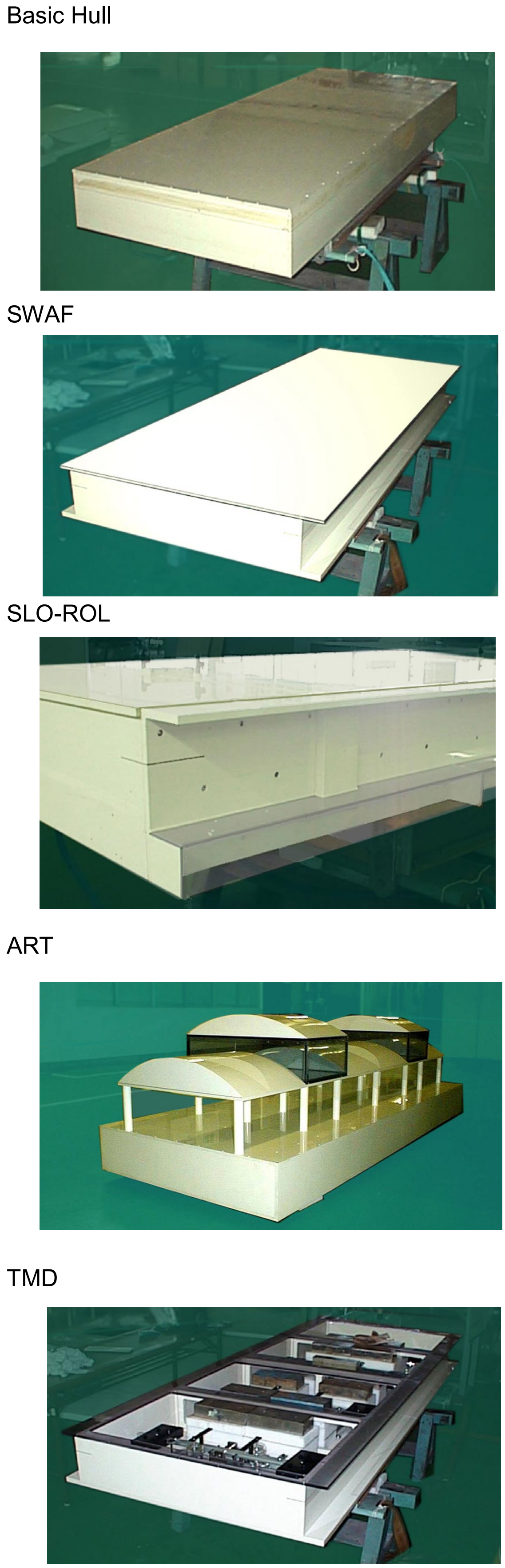

Fig. 2 Tested models

(4) TMD (Tuned Mass Damper) [8]

The tuned mass damper (TMD) is a dynamic damper which is widely used to reduce the vibration of structures, such as high-rise buildings and bridges, due to strong wind or an earthquake. The proposed TMD consists of a dynamic system with a mass, damper and spring, as shown Fig. 1.

By adjusting the damping factor and spring constant, the TMD acts as a damper of the roll motion of the hull.

The expected effects produced by the proposed designs on the roll motion characteristics are summarized in Table 3.

3. MODEL BASIN TESTS

3.1 Outline of the Model Tests

Model tests were conducted to confirm the performance of the proposed motion suppression systems. The tests were carried out using a two-dimensional wave basin 35 m long, 2.5m wide and 1.2 m deep, at Nagasaki Research & Development Center of Mitsubishi Heavy Industries, Ltd. The tested models were made of plastics at a scale ratio of 1/15. The length of each model is 2.48m, which corresponds to 38.2m in full scale. The arrangement of the test is shown in Fig. 3. Wave-induced motions were measured under beam sea conditions. The specified water depth of 0.667 m corresponds 10 m in full scale. The tested model was moored by wires and weak coil.

In regular wave tests, the wave height was 0.5 m in full scale, and the wave period was sequentially changed between 3 s to 12 s in order to determine the motion characteristics. Irregular wave tests were carried for the significant wave height of 0.5 m in full scale and the significant wave periods of 4, 6 and 8 s.

The tests were carried on for the basic hull model and the models with each suppression method. The tested model for TMD has the main hull of the SWAF design, as shown in Fig. 2. The main dimensions of the models and the principal dimensions of each suppression system are summarized in Tables 4 and 5, respectively. The values in the tables are converted full-scale values.

Table 3 Concepts of roll suppression methods and its effect on roll motion

	Effect of Suppression Method on Roll		
	Long Natural Period	Heavy Damping	Small Wave Exciting Moment
SWAF	large	little	large
SLO-ROL	very large	large	large
ART	little	very large	
TMD		large	

Table 4 Main dimensions of tested models

		Basic Hull	SWAF	SLO-ROL	ART	TMD
Length	L (m)	37.2	37.2	37.2	37.2	37.2
Breadth	B (m)	15.0	15.0	15.0	15.0	15.0
Waterline Breadth	B_l (m)	15.0	13.0	13.0	15.0	13.0
Draft	d (m)	2.2	2.2	2.2	2.2	2.2
Displacement	Δ (ton)	1,258	1,113	1,167	1,258	1,113
Height of C. G.	KG (m)	1.5	1.6	2.4	3.1	1.7
Metacentric Height	GM (m)	8.1	5.4	2.4	6.5	5.6
Natural roll period	T_{roll} (s)	4.6	5.9	7.7	5.3	5.7

Table 5 Principal dimensions of each suppression system

SWAF	Breadth of bottom fin : 1.0m Thickness of bottom fin : 0.3m
SLO-ROL	Length of each tank : 9.3m Breadth of each tank : 1.0m Height of each tank : 1.0m Duct sectional area/Tank waterplane area : 1/50 No. of unit : 4
ART	Length of each tank : 5.3m Breadth of each tank : 10.0m Height of tank bottom above keel : 6.2m Water depth : 1.5m No. of unit : 2
TMD	Mass of each unit : 20 ton×2 No. of unit : 4

3.2 Test Results

Fig. 4 shows the measured result of roll motions in comparison with the computed ones. In the figure, the roll amplitudes for the wave height of 0.5m are shown for regular waves. The significant roll amplitudes for the significant wave height of 0.5 m are shown for irregular waves.

The test results for regular waves indicate that the improved hull configuration through the use of each proposed design exhibits good roll motion characteristics. The SWAF and SLO-ROL designs produce a significant shift in the natural period of roll. In particular, this effect is significant with the SLO-ROL design. The ART and TMD designs result in large damping of the roll motion. In the present study, the TMD design is applied to the main hull of the SWAF design. Therefore the test results for TMD include the effects of the SWAF design.

The test results for irregular waves prove that roll motions are considerably reduced in the wave period range of less than 6 s. Better performance is recognized with the SLO-ROL design.

3.3 Theoretical Calculation

The theoretical calculations were performed by a three-dimensional panel method based on the linear potential theory. The potential theory does not satisfactorily predict the roll motion, because viscous damping effects are large. Approximate roll viscous damping effects are calculated by the method of equivalent linearization. The roll suppression concept is treated as an added dynamic system to the main structure.

Fig. 4 shows that the computed results agree well with the measured ones. The calculation method applied to the present study is verified experimentally. The theoretical prediction method can be used to achieve the optimum design of the proposed suppression methods for a variety of hull configurations and wave conditions.

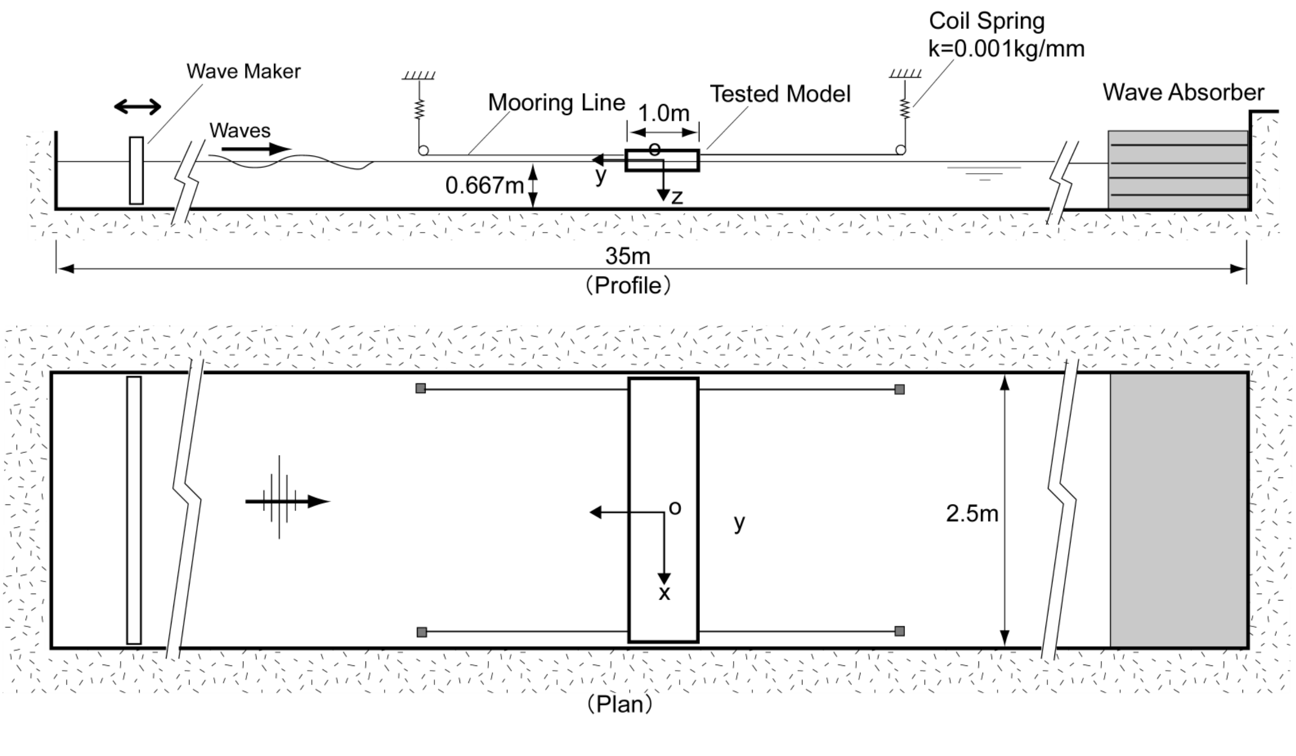

Fig. 3　Arrangement of the model test

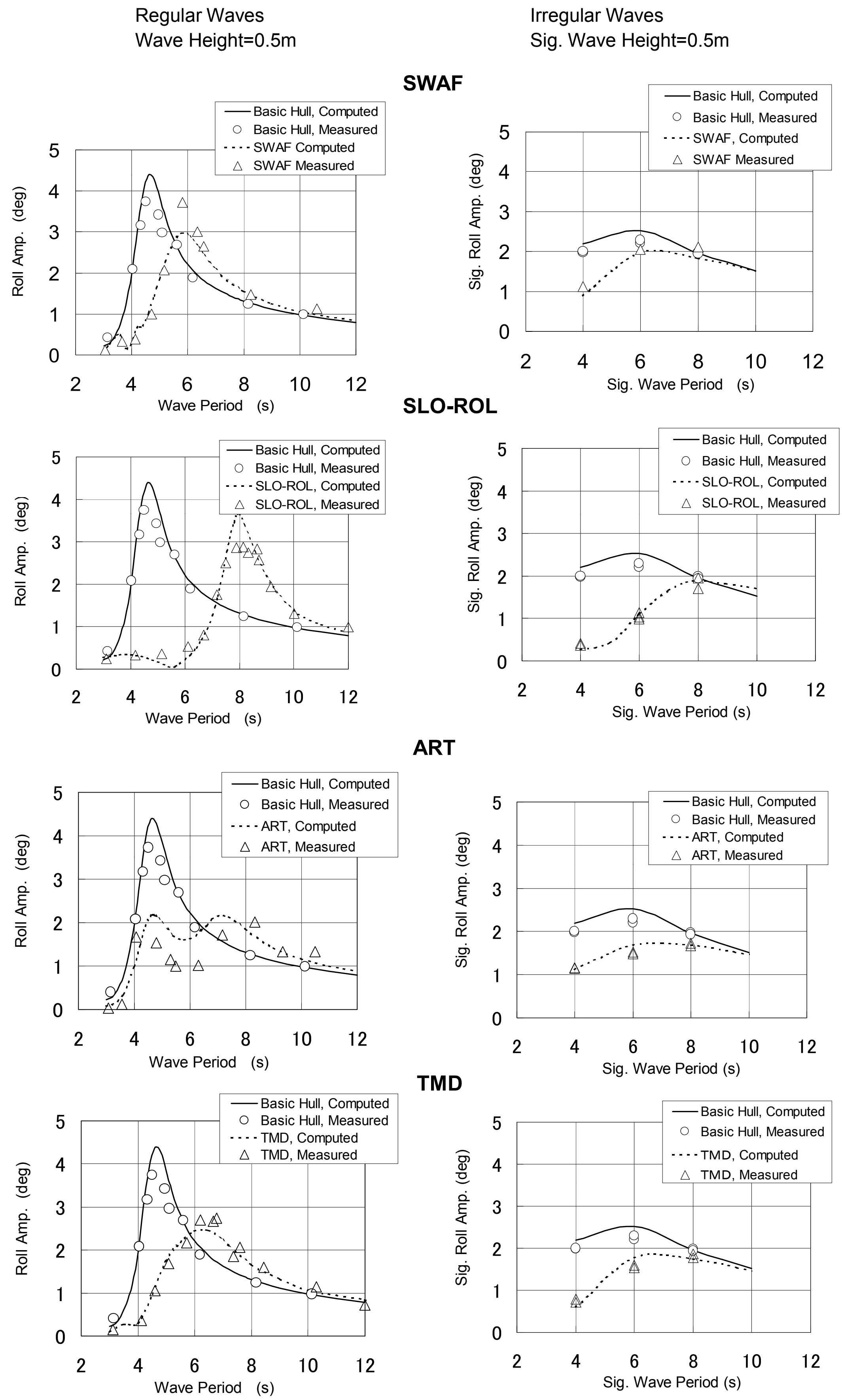

Fig.4 Measured roll responses in regular and irregular waves compared with computed ones

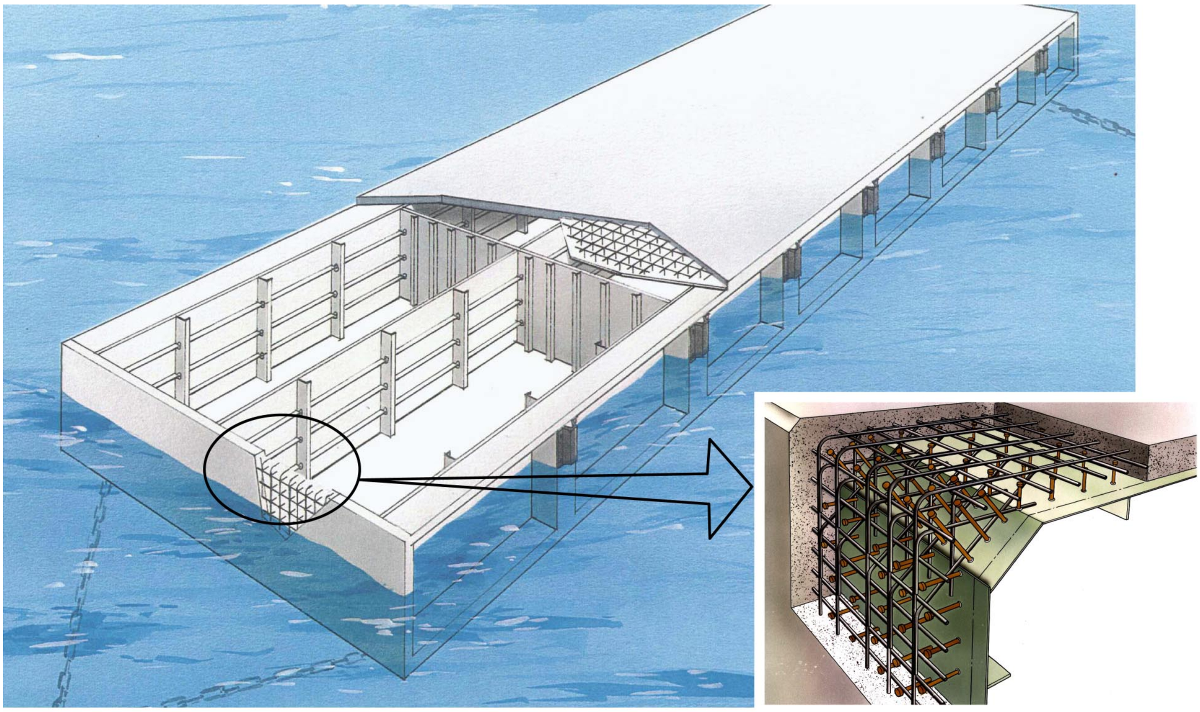

Fig. 5 The SWAF concept applied to a floating pier with a hybrid structure of steel and concrete

4. EVALUATION OF APPLICABILITY

The SWAF design provides the simplest and most reliable hull form. Therefore, it is regarded as a new basic hull form, and can be combined with other designs to achieve better performance. Fig. 5 shows the SWAF design applied to a floating pier, which is designed as a hybrid structure of steel and concrete.

The SLO-ROL, ART and TMD designs are more complex than SWAF, however there is no major problem in putting the proposed designs to in the practical application of the proposed designs. Fig. 6 shows cost estimates for the proposed design compared with the basic hull form. The increment of cost caused by adopting the present designs is small.

The proposed roll suppression systems may be technically and economically viable in small- and medium- sized floating structures.

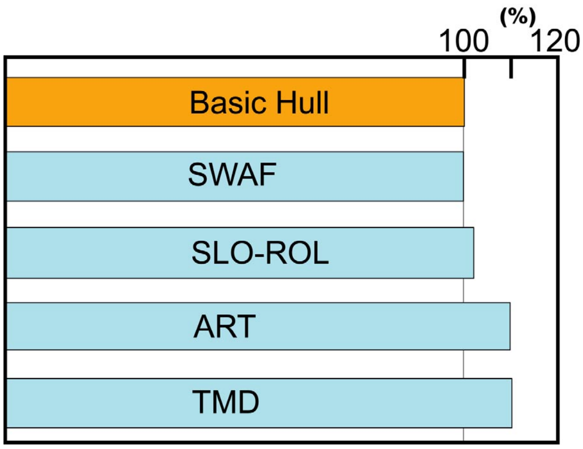

Fig. 6 Cost estimates for the concepts compared with the basic hull form

5. CONCLUDING REMARKS

The results of this study are summarized below.

(1) The following four new designs were developed or improved as roll suppression methods based on passive systems applied to small- and medium-sized floating structures.
- SWAF (Small Waterplane Area with Fin)
- SLO-ROL
- ART (Antiroll Tank)
- TMD (Tuned Mass Damper)

(2) Good roll motion characteristics as a result of adopting each design were confirmed by the results of model tests.

(3) The usefulness of the theoretical prediction method was verified experimentally.

(4) The proposed designs are cost effective and applicable to small-sized floating structures requiring a low cost system.

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REFERENCES

(1) Sellers, F. H. and Martin, J. P., "Selection and Evaluation of Ship Roll Stabilization Systems," *Marine Technology*, Vol. 29, No. 2, 1992

(2) Michael, F. Y. and Waller, D. B., "A New Monohull Form Development as Applied to an Offshore Drilling Unit," *Marine Technology*, Vol. 23, No. 1, 1986

(3) Matsuura, M., Isozaki, Y., and Ishibashi, Y., "Development of Mono-Column Type Hull Form with Passive Type Motion Damping Devices for Floating Production System," *Proc. of the 14th International Conference on Offshore Mechanics and Arctic Engineering*, Copenhagen, 1995

(4) "New Motion Suppression System for Drilling Rigs," *Ocean Industry*, November, 1979

(5) Numata, T. and Kudo, K., and Sao, K., "Study on Motion Suppression System for Marine Structures," (in Japanese) *Journal of the Society of Naval Architect of Japan*, Vol. 157, 1985

(6) Takahashi, T. and Imaizumi, Y., "Experimental Study on Coupled Motion of Ship and Tank Liquid in Waves," (in Japanese) *Journal of the Society of Naval Architect of West Japan*, Vol. 71, 1985

(7) Stinger, Ir. C., "The Performance of U-Tanks as a Passive Anti-Rolling Device," *International Shipbuilding Progress*, Vol. 13, No. 144, 1966

(8) Abiru, H., Harada, H., Tamura, K., Matsumoto, T., and Kondo, H., "Preventing Vibration in High-Rise Structures," *Mitsubishi Heavy Industries Technical Review*, Vol.28, No.2, 1991